Development and Flight Demonstration of a Variable Autonomy Ground Collision Avoidance System

Mark A. Skoog[1]
NASA's Armstrong Flight Research Center, Edwards, CA, 93523

James L. Less[2]
NASA's Armstrong Flight Research Center, Edwards, CA, 93523

Controlled flight into terrain (CFIT) remains a leading cause of fatalities in aviation. Although enhanced ground proximity warning and terrain awareness and warning systems have virtually eliminated CFIT for large commercial air carriers, the problem still remains for fighter aircraft, helicopters and general aviation resulting in roughly 90 deaths each year in the United States alone. This paper covers the initial design and evaluation of an improved system for ground collision avoidance that addresses many of the limitations of current technology. The system derives from the automatic ground collision avoidance system that is currently fielding in the USAF's F-16 fleet. This derivative system added special features enabling significant increases in: terrain storage and fidelity, easily tailored and enhanced fidelity vehicle performance modeling, vehicle-appropriate avoidance techniques, enhanced terrain data handling, and use as either a warning system or, when coupled to an appropriate autopilot, an automatic recovery system. To demonstrate the portability of this software based system it was hosted on a conventional smart phone and adapted to and integrated into both a small unmanned aircraft as well as a Cirrus SR22. Limited flight evaluations were conducted on both aircraft indicating promising advancements in CFIT protection, resistance to false warnings when operating in and around rough terrain. The goal is to create a useful safety enhancement, using portable mobile technology at an affordable cost.

Nomenclature

ACAT	=	automatic collision avoidance technology
AFTI	=	advanced fighter technology integration
AGL	=	above ground level
ART	=	available reaction time
Auto GCAS	=	automatic ground collision avoidance system
CFIT	=	controlled flight into terrain
DTED	=	digital terrain elevation data
DTM	=	digital terrain map
DSOC	=	defense safety oversight council
FPM	=	feet per minute
FRRP	=	fighter risk reduction program
GA	=	general aviation
GPC	=	general purpose computer
iGCAS	=	improved ground collision avoidance system
MSL	=	mean sea level
NASA	=	national aeronautics and space administration
PVI	=	pilot vehicle interface
TCB	=	terrain clearance buffer
UAV	=	unmanned air vehicle

[1] Project Manager & Principle Investigator, Automatic Systems Project Office, P.O. Box 273 / M.S. 2332.
[2] Project Pilot, Automatic Systems Project Office, P.O. Box 273 / M.S. 2332.

USB	=	universal serial bus
VTOL	=	vertical takeoff and landing

I. Introduction

A. Mishap Statistics

The civil community defines Controlled Flight into Terrain (CFIT) as the category of aviation accident where a properly functioning aircraft under the control of a fully qualified and certificated crew is flown into terrain with no apparent timely awareness on the part of crew. From 2001 to 2011 slightly more than one in six fatal general aviation (GA) accidents was attributed to CFIT[1]. With 5,518 deaths in GA aircraft occurring between 2001 and 2010[2], CFIT contributed to roughly 90 deaths a year in the US. The Department of Defense has a similar though slightly different definition of CFIT with the addition of categories such as of g-induced loss of consciousness. Between 1992 and 2004, CFIT within the fighter/attack class of aircraft alone accounted for 41 of the USAF's fleet wide 126 fatalities[3].

B. Previous Development History

The pedigree of this system covered within this paper dates back to 1985 on the Advanced Fighter Technology Integration (AFTI) F-16 program. While developing a suite of systems automating many of the attack features of the F-16, General Dynamics under the direction of the Air Force Research Laboratory, developed an automatic ground collision avoidance system (Auto GCAS)[4]. This system came about solely for flight test safety to protect against undetected single-thread avionics failures that could drive the aircraft into the ground before the pilot could react and regain control from the automatic attack system. This initial Auto GCAS only functioned over smooth terrain and across a limited portion of the F-16's flight envelope. As the AFTI/F-16 program continued automated system development transitioning to Lockheed Martin as the designers, more automation and avionics advancements were added to the aircraft. As these advancements came about, so too did the Auto GCAS such that by 1998 a full envelope, all terrain Auto GCAS had been developed and a comprehensive evaluation was conducted[5].

In 2003 the Secretary of Defense issued a mishap reduction memo calling for a 50 percent reduction in fatal mishaps Department wide. The Defense Safety Oversight Council (DSOC) was established under the Undersecretary of Defense for Personnel and Readiness to address the memo. The DSOC identified Auto GCAS as a required technology to achieve the mishap reduction goal for aviation[3]. The Fighter Risk Reduction Project (FRRP) was initiated to meet this need. In 2010 the fighter risk reduction program completed the research and development of Auto GCAS for fighters[6] and the technology transitioned to the production community with USAF F-16 fielding scheduled to complete in 2014.

C. Drivers Leading to this Development

At the conclusion of the 1998 Auto GCAS program it was identified that the software of the system's algorithm was structured in a way that was conducive to making design changes[5]. Specifically requiring less engineering effort in both design as well as verification and validation testing than was typical for flight software. It became a requirement under the fighter risk reduction program for the software to have a modular architecture such that platforms beyond the F-16 would maximize benefit from the development effort. Schedule pressures to meet the production F-16 software insertion date precluded much scrutiny of the Auto GCAS modular architecture requirement, however the program continued to consider the system as a modular architecture and easy to adapt to other platforms.

D. Content of this Paper

In 2011 NASA approached the DSOC with a proposal to test and evaluate the modular architecture by adapting it to a small unmanned air vehicle (UAV) and conducting a limited flight evaluation. The Armstrong Flight Research Center would assume complete control of the Lockheed algorithm. The objective of this project was to evaluate both the adaptability of the design to a vehicle much different from the F-16 and also the reuse of the software by another designer. Flight test of the resulting system was conducted in 2012.

Following the small UAV project, the DSOC funded a study to verify that the small UAV Auto GCAS design would still support an F-16. This was a paper study conducted in 2013.

NASA's Langley Research Center approached the Armstrong team in 2013 challenging them to adapt the small UAV system to their Cirrus SR-22 (a vehicle with surrogate UAV capabilities). Very limited time and resources were available for the effort. This seemed appropriate for the intent of the design. The software adaptation and two brief flight campaigns were accomplished in late 2013.

This paper covers the work that ensued following the fighter risk reduction program to the conclusion of the Cirrus SR22 effort. The design of the system underwent considerable changes and a distinction between it and the Auto GCAS of the fighter risk reduction project was warranted. The name given to this evolution of the design was the improved ground collision avoidance system (iGCAS).

II. Body

A. Requirements

There were six top level requirements for the iGCAS. Three of these requirements apply to any GCAS design. Stated in order of priority these are: 1) Do No Harm, 2) Do Not Impede and 3) Prevent Collisions. iGCAS had the additional requirements of: 4) a Modular Architecture, 5) Affordability and 6) a Light Weight design.

1. Do No Harm

The system shall not send the aircraft into a situation that is more hazardous than its current state. Subcategories under this include monitoring system health and not directing the aircraft flight path into a collision with terrain or another aircraft when it was originally not at risk of a collision. For both the small UAV and Cirrus SR22 designs this requirement was limited to data and integrity checks through checksums.

2. Do Not Impede

The aircraft shall be able fly under all normal operating conditions without issuing false avoidance commands. This requirement translates to flight at some altitude above the ground in and around various types of terrain. It was decided at this stage of the iGCAS to not yet address suppressing avoidance commands on landing. For UAVs low altitude flight is not a common practice, so for this evaluation it was decided to see how low the aircraft could fly before avoidance commands began to occur. For the Cirrus SR22, flight down to 500 feet from terrain was chosen as to where avoidance commands should not occur.

3. Prevent Collisions

If the aircraft is under controlled flight and both the Do No Harm and Do Not Impede requirements can be met, then and only then avoid collision with the terrain. Collision avoidance is an emergency action to avoid loss of life or aircraft damage. It is not intended to provide “comfortable” separation. Comfort is both pilot and mission relative. Preventing collisions is however in direct conflict with the do no impede requirement. To find the sweet spot in between these two requires that the system provide <u>a timely initiation of an effective and aggressive avoidance maneuver</u>.

For both the small UAV and Cirrus SR22 designs the prevent collision requirement was limited to evaluating a selection mishaps with varying terrain types and meteorological conditions. It was decided at this stage to not yet address obstacles or downdrafts near ridgelines.

4. Modular Architecture

The software shall be easily modified and reused by other designers. The F-16 Auto GCAS code was to be used as the baseline for the system.

5. Affordability

The out of pocket expense for bringing the capability onto the aircraft shall be no more than $100. This requirement was derived to support general aviation pilots.

6. Light Weight

The system shall add no more than 2 pounds to the overall weight of the aircraft. This requirement was derived to support UAV aircraft.

B. Test Articles

The ground collision avoidance system was adapted and integrated into two different vehicles, a small UAV and a Cirrus SR22.

1. The Small UAV

The Dryden Remotely Operated Integrated Drone (DROID) aircraft was used for these tests. It was a 58 pound aircraft with a 9 foot, 8 inch wingspan and an 11 horsepower engine that could fly at speeds between 35 and 80 knots. UAV command and control was provided through a standard Piccolo II system which allowed three different modes of control. Two modes were through a command and control link with keyboard and mouse or pilot flown, both from the ground control station. A third mode of control was available through a hand-held remote control. Ground control station commands to the aircraft could be disengaged through a switch on the remote control.

The vehicle was chosen for its dramatic differences to the F-16 (Figure 1). The vehicle’s intended use was as an MQ-9 trainer. The pilot vehicle interface as well as the flying qualities could roughly approximate that of an MQ-9.

2. The Cirrus SR22.

The Langley Research Center in Virginia supported these tests with a modified Cirrus SR22[7] (see Figure 2). The vehicle has been modified to create a testing capability for UAS technologies and concept in a realistic environment. With a safety pilot onboard, the aircaft can be flown as a Remotely Piloted Aircraft or autonomously from onboard or ground computers. The aircraft has been used as a surrogate UAV for testing onboard sense-and-avoid and separation assurance algorithms. The existing Cobham S-TEC 55X two-axis autopilot has been modified to receive external commands from an onboard research computer termed the general purpose computer (GPC). The aircraft also has a Langley-developed auto-throttle that can also be commanded by the GPC. The research system allows for speed, altitude and heading control form allowing for speed control and altitude control. The GPC control of the aircraft can be replaced with wired or wireless mobile devices.

Figure 1. Small UAV test bed sitting next to F-16 test bed

Figure 2. Cirrus SR22 test bed

C. Design

1. Overall Algorithm

The iGCAS is comprised of both hardware and software. Although both of these are important, most of the focus for this paper will be on the software. At the heart of the software is the decision logic or algorithm that evaluates the situation and decides when an avoidance maneuver is needed.

Although the iGCAS was base-lined off of the FRRP algorithm, many changes were made. The resulting design was significantly different from the F-16 Auto GCAS and thus a different name, the improved ground collision avoidance system (iGCAS) was coined for it to avoid confusion with the F-16 system.

The iGCAS algorithm is structured by functionally partitioning the software into separate modules, each module with an interface that should not require changes as aircraft and requirements change. By containing each collision avoidance function in a separate software module, requirements changes, software changes and retest of those changes can be predominantly isolated to an individual module. The iGCAS functional partitioning is pictured in Figure 3. The *Sense Own State*, *Sense Terrain* functions and *Pilot Controls* are inputs to the collision avoidance algorithm. The command to initiate an avoidance and system status notifications are outputs going to the *Avoid* and *Notify* functions respectively.

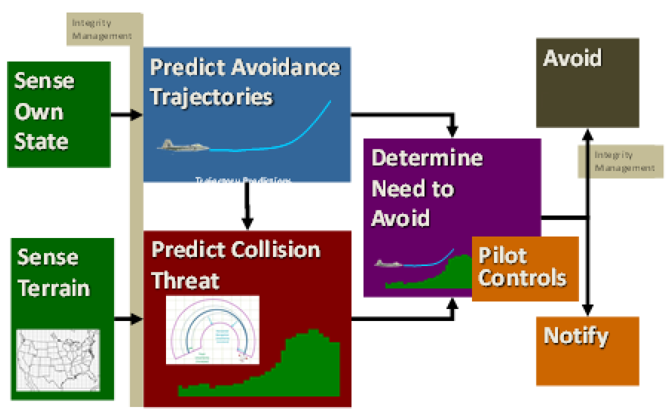

Figure 3. Algorithm functionally partitioned architecture.

Attention is placed throughout the algorithm on precision and agility. Algorithm agility is the computational frame rate and the ability to quickly react to a changing situation. As the aircraft maneuvers through the environment, speed, rates and attitudes of that aircraft are continuously changing. These changes affect the path and duration of possible avoidance maneuvers as well as their final climb rate. Similarly, the environment or features immediately surrounding the aircraft that it could collide with are changing as it flies. The need for precision adding more code to model the details of the avoidance maneuver flight dynamics competes with computer resources and can slow computational frame rate. Slower frame rates mean greater uncertainties for predicting avoidance trajectories and the surrounding environment and thus reducing the system's ability to react in a timely manner.

2. Pilot Interface

Pilot controls were kept to a minimum for development purposes. The controls allowed the system to be turned on and off as well as the entry of a terrain clearance buffer (TCB). The TCB was a flight test tool to artificially raise the ground to allow flight test at farther distances from the ground while the system was still unproven.

3. Avoidance Maneuver

The avoidance maneuver was unique for each aircraft tested being tailored to "aggressive" for that vehicle's maneuvering performance. The definition of aggressive is vehicle dependent, being affected by rates and speeds that the vehicle can generate. For example, an F-16 can generate climb rates well in excess of 30,000 feet per minute where many general aviation aircraft are typically limited to 2,000 feet per minute or less.

Small UAV.

The rates of the avoidance maneuver for the small UAV were chosen to both parallel the F-16 maneuver of FRRP and to model a maneuver similar to what an MQ-9 could execute. This maneuver was to:

1) Roll to wings level to orient the lift vector vertically (the same as the F-16 maneuver)
2) Achieve a climb rate of 1000 feet per minute
3) Achieve 60 knots indicated airspeed (a speed in the middle of the vehicle's envelope)

Because of the limited climb performance, it was decided that additional avoidance maneuvers (termed multi-trajectory) should be added to the system for evaluation. These maneuvers were left and right climbing turns defined as follows:

1) Roll to 40 degrees of bank (left and right)
2) Achieve a climb rate of 800 feet per minute
3) Achieve 60 knots indicated airspeed

These maneuvers were programmed into the flight control computer utilizing the stock bank angle, climb rate and speed capture autopilot loops available in the Piccolo II.

Cirrus SR22.

The Cirrus SR22 variant of iGCAS (iGCAS/SR22) did not use an autopilot and instead relied on the pilot to fly the avoidance maneuvers. Therefore, the avoidance maneuvers needed to be suitable for a general aviation pilot to execute and not become disoriented or over maneuver and end up at an unusual attitude. The multi-trajectory approach was retained. However, where the small UAV maneuvers had very constant rates due to its limited flight envelope, the SR22 rates reflected the aircraft's true climb limits. Purdue University, in conjunction with the FAA's Small Aircraft Directorate developed an avoidance maneuver approach basing it on a modified Chandelle maneuver[8]. The maneuvers chosen for the SR22 were:

1) Roll to wings level or 30 degrees left or right (straight left or right maneuver respectively). 30 degrees bank was chosen to reduce chances of over banking into an unusual attitude.
2) If more than 10 knots above Vy speed (best rate of climb speed), rapidly increase pitch to bleed speed. Near Vy+10 knots, achieve the maximum climb rate that Vy+10 knots can be sustained.
3) Select full throttle.

iGCAS/F-16.

The F-16 Auto GCAS utilized only one avoidance maneuver (a rapid roll to wings level and pull to between 5 and 6 g's or near-maximum angle of attack. The pull continued until the aircraft velocity vector was clear of the terrain ahead of the aircraft. In adapting a multi-trajectory avoidance to the F-16 iGCAS, it was desired to keep the straight maneuver identical and to have the turning trajectories use similar rates to that of the straight trajectory. This would allow for a more direct evaluation of the advantages of using a multi-trajectory solution over the single trajectory of the Auto GCAS.

The F-16 turning maneuvers chosen were as follows:

1) Roll to 45 degrees of bank in the desired direction of turn.
2) Pull to the same load factor as the straight avoidance maneuver.
3) As with the F-16 Auto GCAS maneuver, throttle is to remain constant while in a dive allowing speed to increase or decrease according to aircraft state and configuration. As the flight vector passes above the horizon, MIL thrust is selected.

4. Sense Own State

Primary inputs to the algorithm are geo-referenced position (latitude, longitude and altitude), aircraft rates (climb rate and roll rate), velocity vector information (ground track and true airspeed), bank angle, parameters affecting the performance of the aircraft (indicated airspeed and density altitude) and horizontal winds.

5. *Trajectory Prediction*

The *Predict Avoidance Trajectories* function simulates the avoidance maneuvers ahead of the aircraft producing a geo-referenced 3-dimensional trajectory. Three axes are computed in the kinematic model, roll, pitch and speed. Range and ground track are derived from these. A typical maneuver time history and the associated trajectory prediction are shown for both the small UAV and SR22 in Figures 4 & 5.

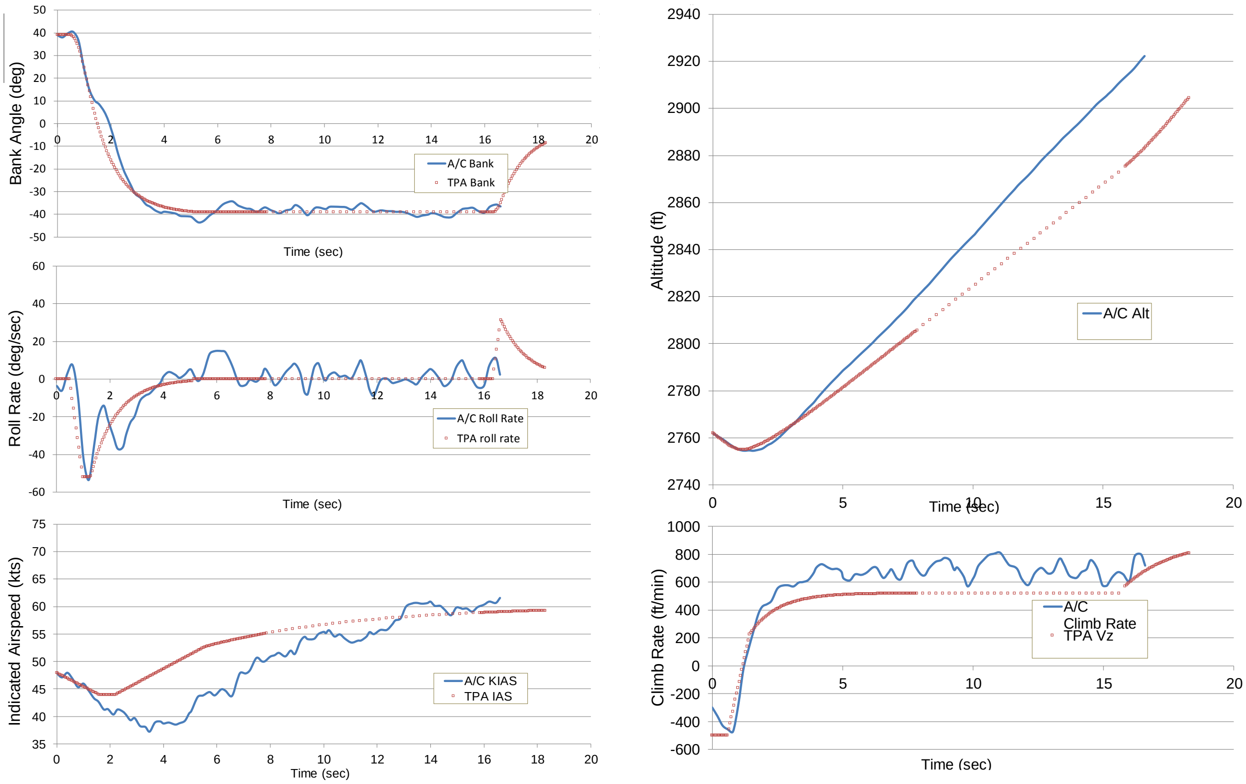

Figure 4. Typical iGCAS Small UAV trajectory time history.

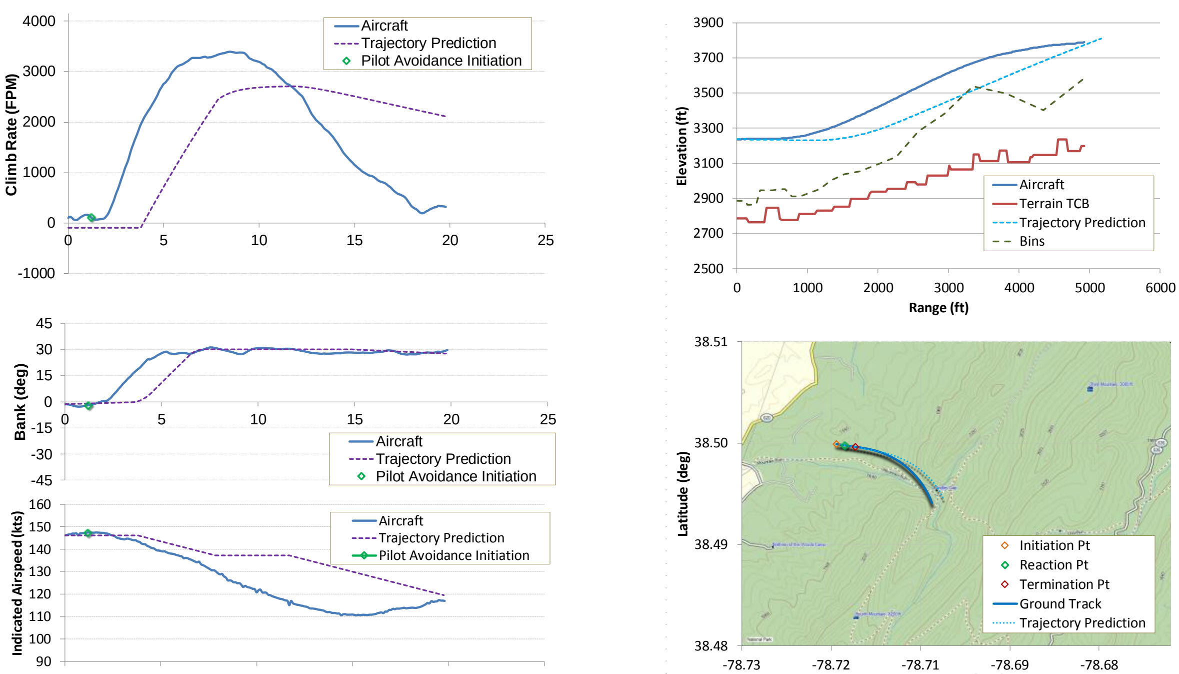

Figure 5. Typical iGCAS SR22 trajectory time history.

For the small UAV and SR22 the vertical part of the trajectory prediction, climb rate was used rather than vertical load factor as used by the F-16. This was chosen because it was the primary loop closure in the autopilot and the slower speeds and lower climb rates of the small UAV relative to the F-16 meant the recoveries would have a larger proportional time during the sustained climb phase than for the pull up phase.

The SR22 trajectory prediction added additional delay to account for pilot reaction time. This was the only change within the algorithm required to convert it from supporting an automatic system to a manual warning system. The target climb rate for the SR22 trajectory prediction was changed to a schedule based on the aircraft manual[9]. Climb rate dynamics were also modified to reflect the modified Chandelle maneuver.

The F-16 variant of iGCAS (iGCAS/F-16) utilized a trajectory model with a slightly different control loop for pitch. Because the F-16 autopilot uses vertical load factor as the primary control parameter, vertical load factor was used in the trajectory model instead of climb rate as in the SR22 and small UAV.

6. Sense Terrain

Sensing ground proximity utilizes a digital terrain map (DTM) product and a map manager routine to store and retrieve terrain elevations. A two-step process is used. First the stored data set (called the "gaming area") is selected and brought into the GCAS non-volatile memory. Secondly a subset of these data surrounding the current aircraft position are retrieved and used to generate a "local map" in RAM during flight. The local map is periodically updated as the aircraft flies, discarding the data that is well behind the aircraft and retrieving new data that lies some distance ahead of the aircraft.

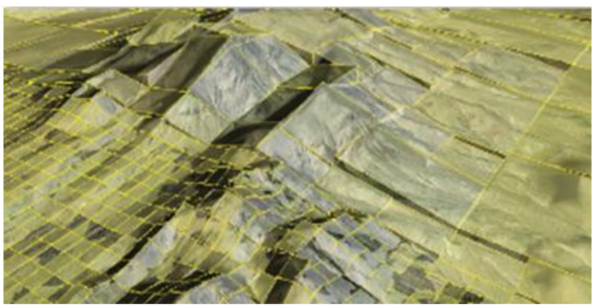

Figure 6. Example of encoded Terrain data.

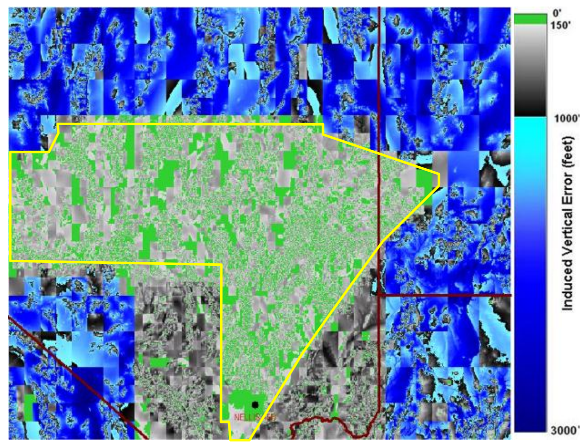

Figure 7. Semi-regular terrain data with corresponding elevation data from source data.

The same DTM resolution used in the F-16 Auto GCAS (3 arc-seconds) was chosen to be used inside the iGCAS, however terrain-fidelity was increased and file size reduced. To address the issues of file size, resolution, fidelity and coverage, a digital terrain encoding routine was developed that merges any number of DTM products to create a "best available" global DTM at any desired resolution with easily user defined geo-referenced variable fidelity that requires a minimum file size. The process and software product that embodies this generates a semi-regular array of data. Figures 6 shows an example of the resulting product in yellow. This encoding process results in a semi-regular array of data with tile sizes of different sizes. Figure 7 shows a geo-referenced difference plot between the source data and encoded product around the Nellis air force based area. The

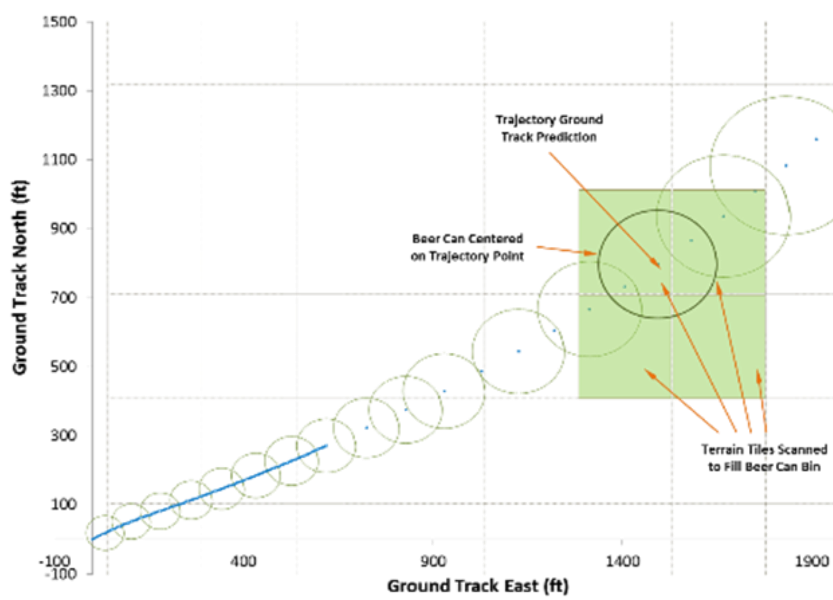

Figure 8. iGCAS scan and scan-cylinder filling.

encoding process reduces terrain fidelity while maintaining accuracies to the source data according to required flight levels. For Figure 7, three different flight levels were required for this area. Flight to 500 feet above ground level (AGL) was required within the yellow boundary, a 2-percent glideslope to 150 feet was required for approach to the runway located at the black dot and 3000 feet AGL flight was required for all other areas. The encoding process matches the original data as closely as possible with a minimum amount of data often exceeding terrain accuracy beyond the required flight level as can be seen by the pervasive green in the 500 foot flight area.

7. Predict Collision Threat

For predicting the collision threat, a terrain profile is generated of the terrain that the each of the avoidance trajectories are predicted to pass over. The DTM is down-sampled to generate these profiles. The iGCAS process differed from the Auto GCAS approach in a number of ways worthy of note. The process began with ground track as identified by the output array from the trajectory prediction defining the centerline about which the DTM would be accessed (scanned) for terrain elevation. Next, a series of circles along the trajectory were defined with expanding radii. The expansion of the circle radii is based on the horizontal navigation uncertainty and the track uncertainty. These circles were used to fill bins with the highest elevation of any local map elevation tile they touched (see Figure 8). Finally, these bins are raised by the vertical navigation uncertainty and the TCB. Figure 9 shows an example of the iGCAS scanning process. The blue lines indicate the track of the three trajectories. The green cylinders show each of the bins and the dark green discs above the bin-cylinders show how the bins are raised by the vertical uncertainty and TCB.

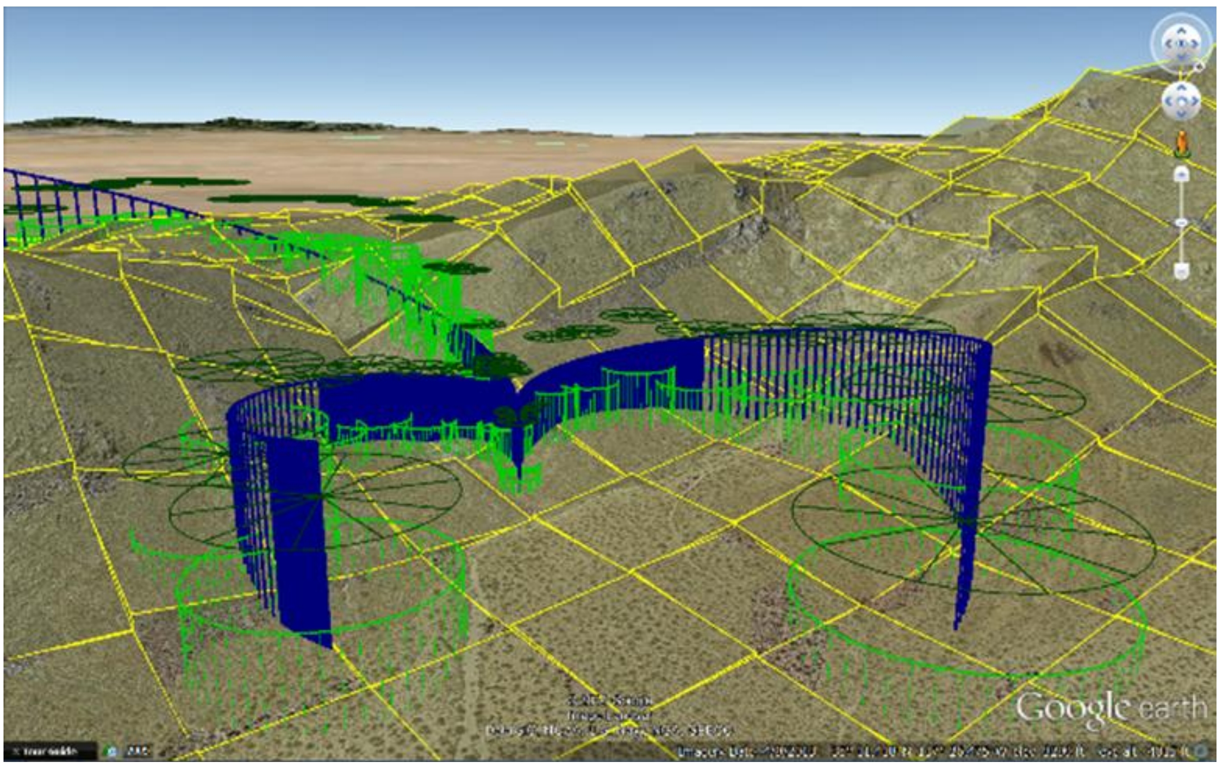

Figure 9. Trajectory-based circular scanning method for left, straight and right trajectories with encoded terrain data displayed.

8. Determine Need to Avoid

The *Determine Need to Avoid* function compares each of the avoidance trajectories to the corresponding terrain profile to determine ground clearance. When the last of the three trajectories no longer clears the terrain, that trajectory was selected as the avoidance maneuver to execute and an avoidance initiation is issued. Once an avoidance initiation is issued, that maneuver remains the selected avoidance maneuver to fly. Maneuver termination occurs when the straight recovery clears the terrain profile.

9. Notify

Each maneuver's viability is displayed to the pilot by a colored block arrow with its corresponding time to avoid value. Arrows were colored green if time to avoid was greater than 5 seconds, yellow if between 0 and 5 seconds and grey if less than 0 seconds unless it was the last viable maneuver and then the arrow was filled with black and white hash (see Figure 10). Avoid was also displayed when an avoidance was being issued. Overall, minimal effort was invested in display development for the iGCAS multi-trajectory system. Pilot interface development is planned for future stages of the system's development.

Figure 10. iGCAS Avoidance Display

10. Hardware.

The iGCAS algorithm was implemented into a DROID 2 cell phone running with Android 2.3 operating system. Java was the coding language used. Data was fed from aircraft systems into the phone via the USB port on the phone. The gaming area map was stored on the micro-SD card within the phone.

<u>Small UAV</u>.

The small UAV Smartphone had two different ways it was integrated with the aircraft. The first was in the ground control station. A user interface computer was hooked up to the ground control computer of the Piccolo II and the phone was hooked to the user interface computer via USB. Aircraft state data were sent from the aircraft through the command and control link of the Piccolo II. Avoidance commands issued by the phone were sent to the user interface computer which converted the commanded maneuver into autopilot settings for the Piccolo II and automatically turned those autopilots on. This integration added no weight to the UAV.

The second integration was onboard the UAV. A Gumstyx computer was also added to the UAV. The phone was connected to the Gumstyx via USB and the Gumstyx was connected to the Piccolo II on the UAV via RS-232. When the phone issued a maneuver initiation request, the Gumstyx set and engaged the appropriate autopilots on the Piccolo II. This configuration allowed iGCAS to provide protection even during lost link situations. All pilot interface was accomplished through the user interface computer on the ground within the ground control station. The on-aircraft installation is shown in Figure 11. Overall weight added to the aircraft for the iGCAS installation was 1.5 pounds.

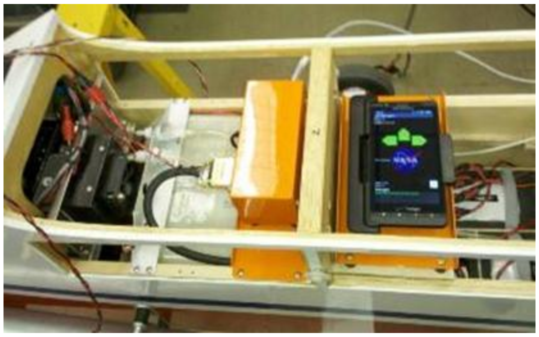

Figure 11. Small UAV On-Aircraft Hardware Installation.

Cirrus SR22.

The Cirrus SR22 interfaced the iGCAS to the aircraft through the general purpose computer (GPC). The GPC had all required aircraft state information and could (if needed) control both the autopilot and auto-throttle. The phone was mounted to the right of the center console (see Figure 12) and connected to the GPC with a USB cable. The GPC was configured to provide all pilot controls to the phone.

Figure 12. Cirrus iGCAS/SR22 phone installation.

D. Test and Evaluation

Testing was conducted on the small UAV and SR22 version in two stages. Flight tests were conducted to first characterize the flight dynamics of the avoidance maneuver of each platform. Avoidance maneuvers were initiated from a variety of flight conditions and flown through extended recoveries to collect dynamic response data. Using the data from a given platform, variables were derived to tailor the trajectory prediction so that it properly modeled that platform's performance characteristics.

Following the characterization flights, the tailored system was evaluated for both collision avoidance prevention and nuisance potential (the tendency to issue warnings when the pilot does not consider ground impact to be imminent).

The iGCAS/F-16 was evaluated differently than the small UAV and SR22 versions of iGCAS. Resources did not allow for the F-16 to be modified with the iGCAS nor flight test to be conducted. Instead, flight test data from the previous Auto GCAS testing were fed into the F-16 version of the iGCAS system and iGCAS outputs were compared to Auto GCAS outputs at situations where Auto GCAS had issued nuisance recoveries.

1. Automatic Avoidance on a Small UAV.

The small UAV flight testing was conducted in and around the Edwards AFB area. 208 collision avoidance recoveries were executed over 21 flights. Terrain features flown at during testing included flat terrain, a small hill with a 67 foot rise and an unimpeded 29 degree slope and a larger area that included a number of features such as 1400 foot rise with a 25 degree slope, a 600 foot rise with a 45 degree slope and a box canyon with up to 500 foot walls.

Overall, the iGCAS/Small UAV demonstrated excellent collision avoidance, adequate Nuisance Potential, and outstanding modular technologies.

Small UAV Charaterization Evaluation

During development of the F-16 Auto GCAS, simulation was used extensively to characterize the avoidance maneuver. No reliable simulation existed for the small UAV. Thus, flight test was used to characterize the avoidance maneuvers. As mentioned above, the autopilot was initiated from numerous flight conditions (airspeed, bank and dive) for each of the three maneuver types. 29 recoveries from portions of three characterization flights were used to

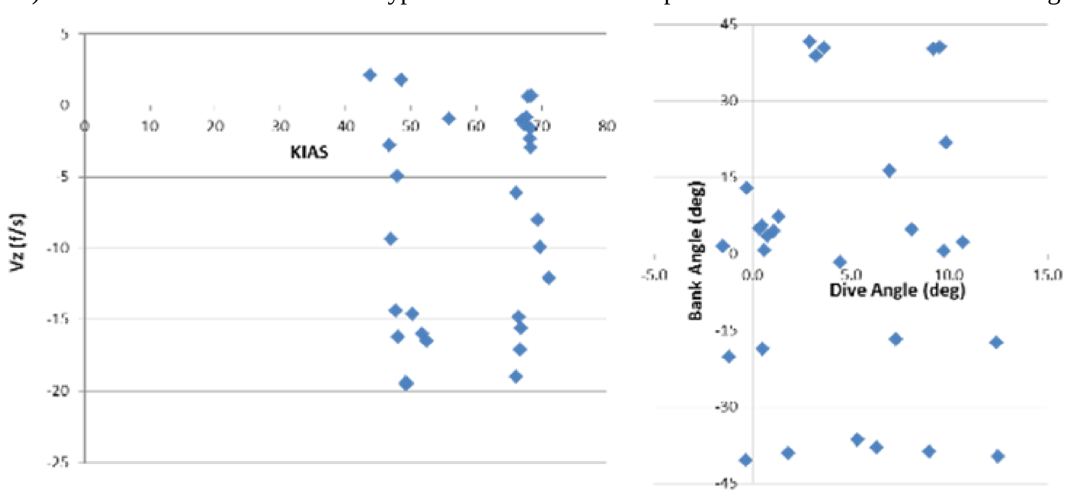

Figure 13. Small UAV characterization flight recovery initiation conditions.

tailor the trajectory prediction. Conditions at recovery initiation ranged from 43 to 71 knots indicated airspeed, 41 degrees left to right wing down bank and 12.5 degrees of dive to 1.5 degrees of climb (see Figure 13).

Figure 4 shows a typical avoidance characterization maneuver with the blue line showing actual aircraft response and the red points showing the trajectory prediction points. The avoidance maneuver was initiated from 45 knots at 40 degrees of bank in a 5 degree dive. Numerous phenomena were found from these tests that resulted in trajectory model changes. These phenomena were:

1) P-Factor. There was a pronounced P-Factor (yawing moment due to applied power from the propeller) effect seen on the small UAV during recovery execution. Turn rates averaged 2.5 degrees per second to the left during wings level climbs (see straight recovery on Figure 9). During turning recoveries this turn rate coupled into climb rate, reducing the climb rate achieved in left wing down maneuvers and increasing it in right wing down maneuvers. As one of the objectives of the small UAV tests was to determine how well the iGCAS could adapt to different aircraft performance, it was decided to not reduce the P-Factor effect by modifying the aircraft or autopilot used. Instead it decided to try to model the effect in the trajectory model.
2) Wind gust response. The low inertia of the small UAV made it highly susceptible to wind gusts. This can be seen in the climb rate and bank traces in Figure 4. When combined with the control logic of the Piccolo II autopilot, the result was a response less than the target for the maneuver. The climb rate in particular was chosen to have a target value of only 80 percent that of the commanded performance capability of the aircraft. This caused a slight under prediction in the long range climb insuring two things: 1) a gust would not force the aircraft significantly lower than the prediction and 2) at some point into the actual recovery the aircraft would be out performing the prediction resulting in a flight path that would be certain to clear the terrain ahead of the aircraft allowing for a more consistent avoidance termination.

iGCAS/Small UAV Collision Avoidance Evaluation

There were a total of 61 ground avoidance “events” that were included in the post-flight analysis process. The remaining avoidance maneuvers were either conducted with development versions of the iGCAS or during the characterization flights. TCBs for the collision avoidance runs ranged from 200 feet to 0 feet. Valid initiations occurred on 52 of the 61 runs. The 9 invalid initiations were induced by residual telemetry problems caused by the command and control link.

The primary measure of CFIT protection is “How close did the aircraft get to the rocks?” This question is answered using the minimum altitude above ground level (AGL) value reached during a recovery. Out of the 52 valid initiations, 42 resulted in avoidance maneuvers being flown to a usable minimum AGL value. Eight cases terminated the avoidance maneuver before a minimum AGL value was reached. On these runs the Safety Pilot took control of the aircraft before reaching the minimum AGL location. In these cases the Safety Pilot took control because the ability to judge terrain clearance was degrading (due to a combination of distance and other terrain in the background), not because of a problem with the trajectory of the Auto GCAS avoidance maneuver. Two of the unusable minimum AGL cases were due to FAIL conditions that were fixed in later software updates.

Out of the 52 valid initiations, 28 continued all the way through normal termination without being interrupted by the Safety Pilot or having telemetry dropout issues.

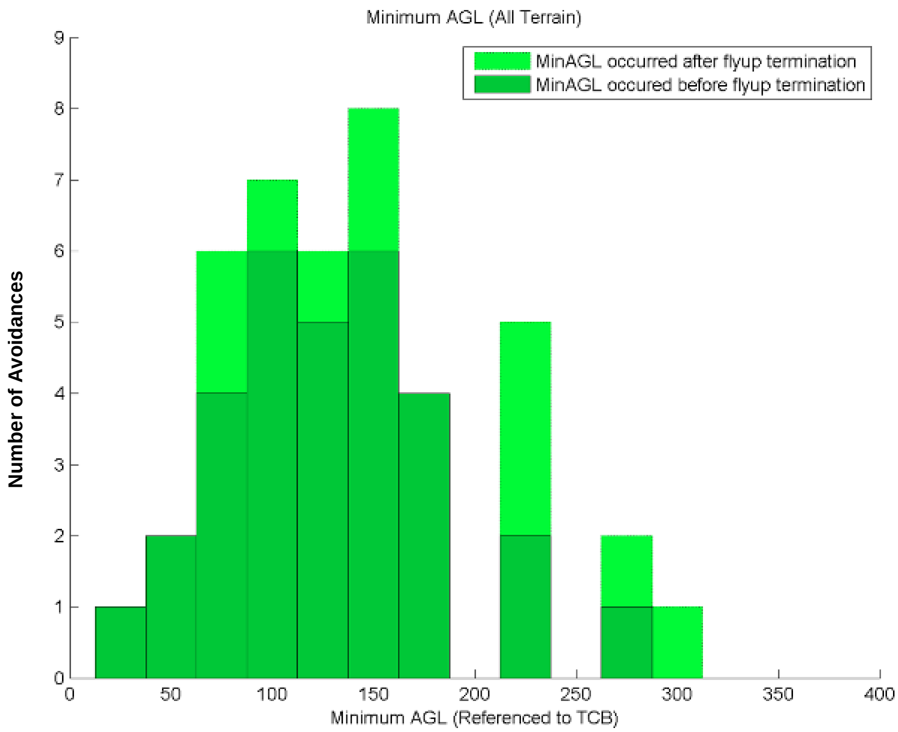

Figure 14. iGCAS/Small UAV minimum approach to TCB.

Figure 14 provides an answer to how close the aircraft got to the rocks using a histogram for all 42 of the runs that resulted in a useable minimum AGL value. It can be seen that most runs cleared the TCB by at least 100 feet and no runs penetrated the TCB. This indicates that the overall design is providing excellent collision avoidance. Further results regarding these test will be published in a subsequent NASA technical manual.

Other sub-component contributors to collision avoidance performance were evaluated. The flight path of each recovery was evaluated against the scan area for the avoidance. Figure 15 shows the farthest excursion from the track prediction for each run plotted relative to a normalized scan pattern. The figure shows 4 runs where the aircraft flew outside of the scan pattern. Three were on the inside of the turning recovery and 1 on the outside of the turn. The location of the trigger post was similarly plotted on the normalized scan pattern and can be seen in Figure 16. This figure shows that often times the post location of the terrain that triggers an avoidance was on the outside of the turning recovery. This makes sense when one considers that the local map is generating a tile at the height of the post and the scan-cylinder is using the highest tile. For runs approaching rising terrain, the critical post was scanned often times as the scan-cylinder first touched the outer edge of the tile. This created an extra buffer and suggests that the 3 runs that had excursions outside of the scan pattern on the inside of the turn would not have run into high terrain as none of the critical posts in Figure 16 were on the inside of the turn. The one point in Figure 15 that fell outside of the scan on the outside of the turn then indicates the only potential problem.

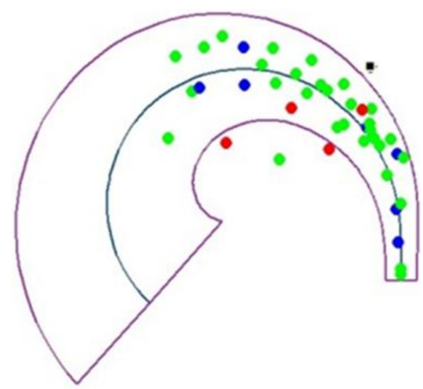

Figure 15. iGCAS/Small UAV worse case trajectory excursion relative to normalized scan width.

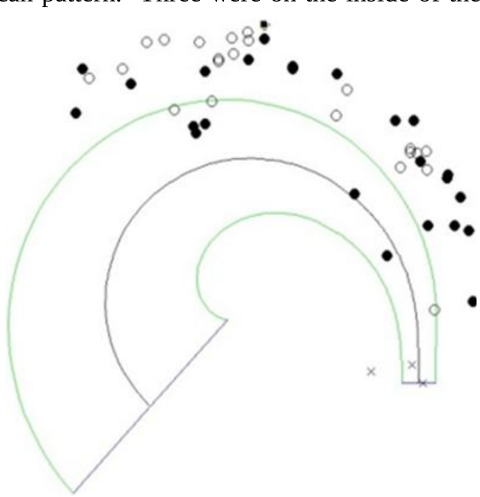

Figure 16. iGCAS/Small UAV trigger post relative to normalized scan pattern.

iGCAS/Small UAV Nuisance Evaluation

Providing a measure of nuisance potential is more problematic than for collision avoidance. Nuisance potential is a more subjective measure that will always depend on the individual operator's perspective and on the mission of a particular aircraft. Previous F-16 testing had used two techniques. One technique involved flying operationally relevant low-level in an aggressive manner to see if nuisance activations occurred. Another method was used where flight data were collected and compared against a nuisance criteria that had been previously developed. Neither of these methods appeared valid for use with UAVs. The criteria method was derived from pilots monitoring approaching terrain by looking out of the cockpit under circumstances of high situational awareness. With the degraded situational awareness that UAVs have regarding visualizing the terrain around the vehicle, this criteria seemed overly harsh for a requirement. The low-level mission method too was not valid because UAVs do not fly low-level missions because of their reduced situational awareness.

What was found from the nuisance evaluation of the iGCAS/Small UAV was that the UAV operator could execute missions much lower than is common for UAVs. The added protection provided by the system increased the mission capability of the vehicle. Runs were also conducted with the turning trajectories turned off and iGCAS only using the straight recoveries. Many nuisance activations were seen in this mode indicating the nuisance free advantage of the multi-trajectory feature.

Nuisance potential was analyzed in a similar manner to that used for the FRRP F-16 Auto GCAS and is presented in Figure 17. These data are presented in the form of available reaction time (ART). ART is the amount of time that the recovery could have been delayed beyond where it was initiated for the recovery to have just scraped the ground at its minimum approach. The data show that iGCAS initiated recoveries with an ART of 1 to 8 seconds. The average ART was slightly less than 4 seconds. Pilots who evaluated the system considered this easily adequate.

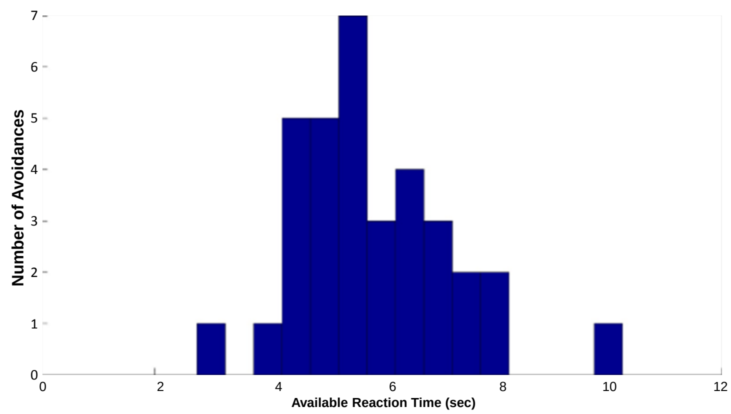

Figure 17. iGCAS/Small UAV available reaction time.

2. Automatic Avoidance on an F-16.

The iGCAS/F-16 evaluation did not include flight testing of the system, it was only done though analysis. Sixteen nuisance recoveries on 5 flights from the ACAT/FRRP evaluation were chosen where the FRRP Auto GCAS had activated during those missions. The conditions from those recoveries were fed into the iGCAS algorithm to evaluate whether or not the iGCAS would have initiated a recovery.

F-16 Characterization Evaluation

Tremendous time was spent developing the trajectory prediction for the FRRP/F-16 algorithm. Resources were not available to undergo a similar effort for the iGCAS trajectory model. However to compare the response of the two systems, all that is required is for the trajectory to match at the specific condition obtained during the FRRP flight. So, tuning of the iGCAS trajectory was done individually for each run. The trajectory variables for iGCAS were adjusted so that the bank, speed and altitude predictions matched those of the FRRP algorithm for each run evaluated. All other aspects of the iGCAS was tailored as closely as possible to that of the FRRP algorithm. The same vertical, horizontal and track uncertainties values were used for iGCAS as were used for the FRRP algorithm. The additional scan width that FRRP used to accommodate high lateral turn rate conditions were not implemented within iGCAS as it was assumed the trajectory-based scan would account for those conditions.

iGCAS/F-16 Collision Avoidance Evaluation

Collision avoidance performance was difficult to evaluate because only nuisance recovery conditions were evaluated. As these did not pose a collision risk and the trajectory was tuned to match the FRRP trajectory no obvious differences would be expected. Each run was evaluated for horizontal excursion from the track prediction and none fell outside of the scan pattern.

iGCAS/F-16 Nuisance Evaluation

Nuisance potential was evaluated using estimated time to avoid for each of the iGCAS trajectories. The iGCAS time to avoid values were evaluated for how far they differed from the FRRP time to avoid value.

It was expected to see similar time to avoid values for the straight recovery of iGCAS to that of the FRRP. This was not the case. In more than half of the cases, the iGCAS time to avoid was positive indicating it did not see a need to begin a recovery. For half of the runs (8 cases) evaluated, it was found that the FRRP algorithm had filled the bin that drove the recovery initiation with a terrain post that was well outside of its scan area (see Figure 18). Unlike iGCAS, this is not how the FRRP scanning logic was intended to function. An erroneous terrain post had been the cause of the recovery activation.

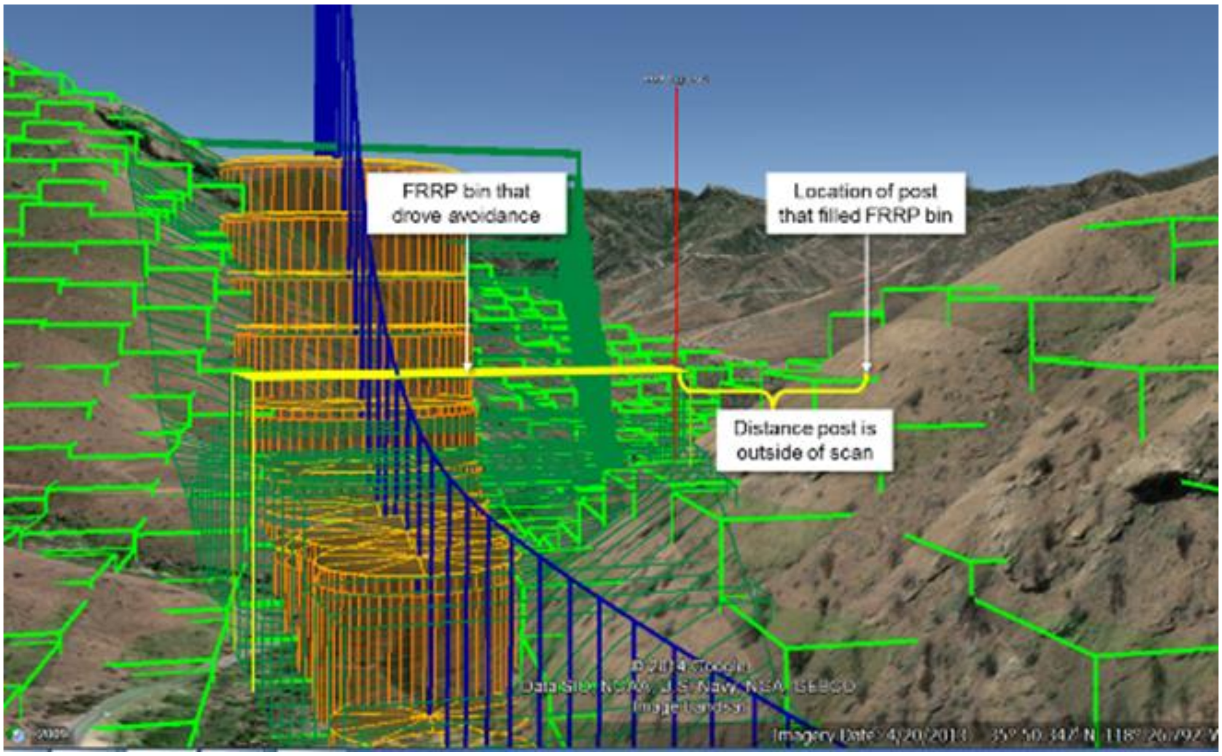

Figure 18. FRRP/F-16 scanning of erroneous terrain post.

Of the remaining runs where FRRP had not used an erroneous terrain post, half of these (4 cases), the straight recovery for iGCAS was still not negative at the avoidance initiation condition. These cases were recoveries that all initiated in a turn. Figures 19 and 20 show an example run. Upon inspection of these figures it can be seen that the iGCAS scan did not capture the terrain post that drove the FRRP bin height that caused the avoidance. As the aircraft was in a left wing down turn at avoidance initiation, the iGCAS trajectory-based scan skewed further to the left than the FRRP scan causing it to not capture the higher terrain that initiated this recovery.

Of the remaining cases evaluated, 2 benefitted from the turning trajectory and would not have activated at the point of FRRP and 2 would have. These two that would have still been nuisance activations were caused by the resolution of the DTED in the local map being too coarse and tile smeared the terrain post to the edge of the iGCAS scan-cylinder causing time to avoid to be negative for all three trajectory options.

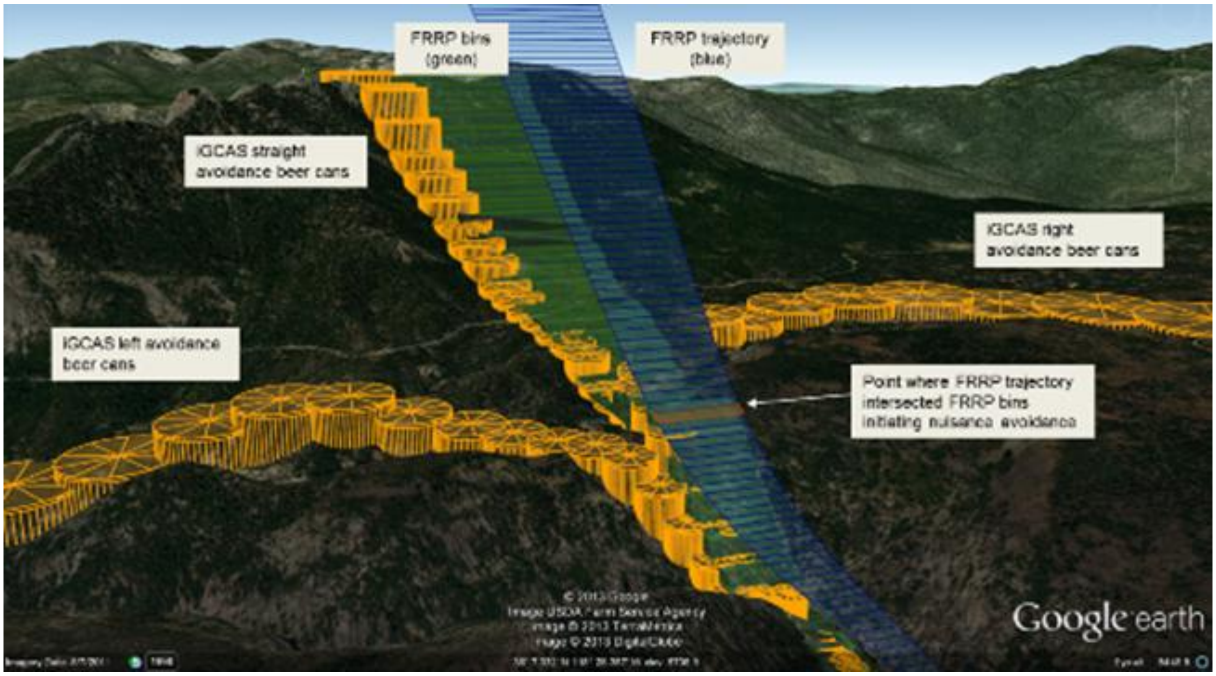

Figure 19. iGCAS/F-16 to FRRP Auto GCAS comparison.

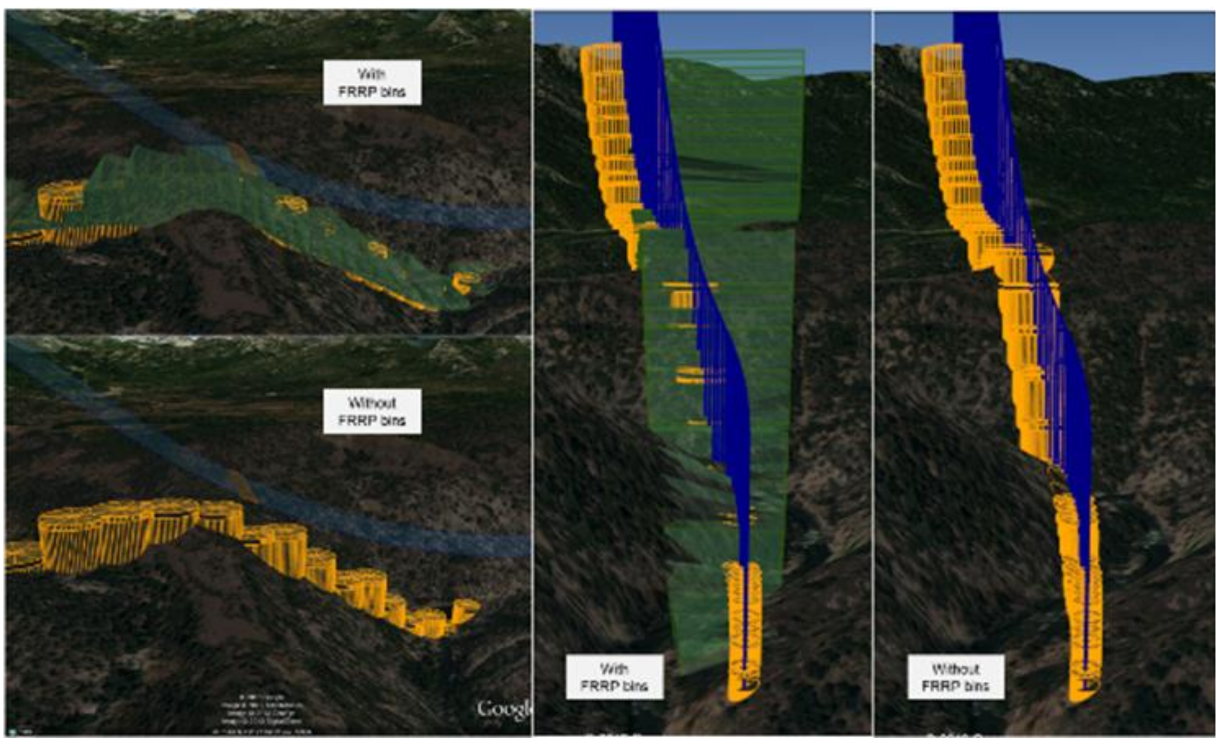

Figure 20. iGCAS/F-16 to FRRP Auto GCAS trajectory-based scan advantage.

3. Pilot Warning on a General Aviation Aircraft.

The SR22 version of iGCAS (iGCAS/SR22) was evaluated on five flight test sorties. Two characterization flights were conducted near the Langley Research Center in Virginia. Three ground collision avoidance flights were conducted in the Shenandoah Valley region of Virginia just north east of Harrisonburg. Simulation testing for ground collision avoidance was conducted both against the same terrain as was used for flight test as well as additional select locations around the country.

The SR22 executed 71 recoveries over 5 flights. Overall, the iGCAS/SR22 demonstrated excellent collision avoidance and adequate nuisance potential as evaluated. Additionally, the integration of the system onto this new aircraft was accomplished with exceedingly few engineering labor hours, and, the system functioned flawlessly on the first flight. These results show tremendous promise for the modular architectures ability to streamline the verification and validation process.

SR22 Characterization Evaluation

A total of 45 avoidance maneuvers were flown at 100 and 145 knots, 1500, 5000 and 10000 feet MSL, left, straight & right to characterize the SR22 performance for tailoring the trajectory prediction in the algorithm. The chosen maneuver for the autopilot was to capture 700 FPM, heading capture of +/- 175 or 0 degrees from current heading to drive bank and 100 knots. These values had been chosen as the closest the autopilot could come to the modified Chandelle maneuver previously mentioned. In the case of these tests 700 FPM was the maximum that could be commanded in the available autopilot on the SR22, heading capture would give the most bank available and 100 knots was chosen for being approximately the Vy climb speed.

Of the 45 characterization runs, 32 were executed using the autopilot. Test results for the autopilot showed very limited turn rate capability and poor consistency in bank and climb rate capture. The limited turn rate capability was attributed to the autopilot limited bank authority. Maximum bank angle during turning runs ranged between 5 and 15 degrees. This resulted in a nominal turn radius of 6000 feet (see Figure 21). The poor consistency in the capture values was attributed to safety features in the computer that interfaced the phone to the autopilot. The test aircraft was primarily used as a surrogate UAV. The interface computer was required to have many safety features that would modify autopilot capture values in real time. These automatic changes to autopilot capture values created an artificial complexity to modelling the avoidance trajectory.

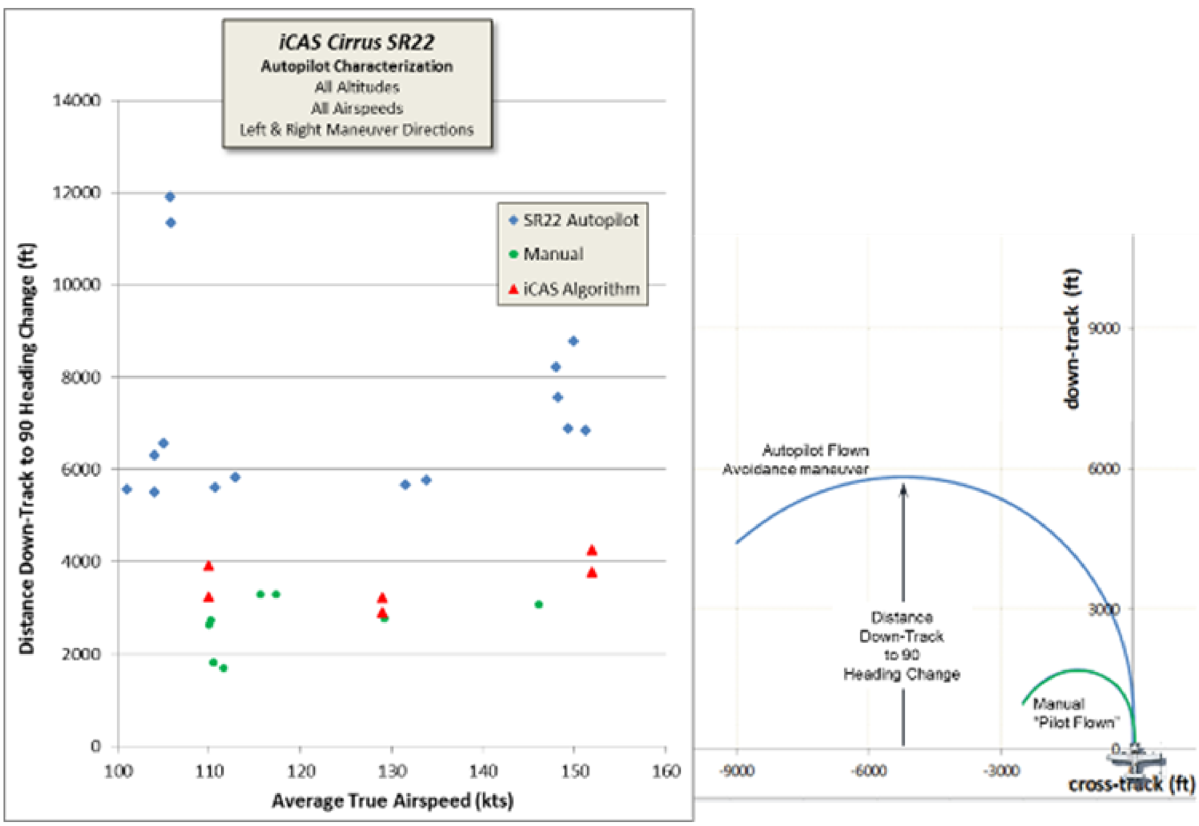

Figure 21. SR22 autopilot and manually flown avoidance turn performance.

The remaining 13 characterization runs were flown manually by the pilot. Test results from these runs showed that sustained climb rates of roughly 1200 FPM +/- 100 FPM. This was in accordance with expected results per the SR22 Flight Manual Section 5 climb performance chart. Peak zoom climb values ranged from 3600 to 2000 FPM. Bank angles achieved were 30 degrees left and 27 degrees to the right +/-3 degrees. Roll rates were roughly 15 d/s to the left and 10 d/s to the right. Slower rates were observed at slower airspeeds than higher airspeeds. Sustained airspeeds during the sustained climb phase were 97.5 knots +/-2 knots and airspeed bleed during the zoom climbs ranged between 2 and 3 knots per second. The turning runs had a turn radius between 2000 and 3000 feet for all airspeeds.

In summary, the manually flown avoidance maneuvers significantly outperformed the current autopilot, due to the limited authority. This combined with the greater consistency of the manually flown maneuvers, it was decided to tailor the iGCAS trajectory to the manual maneuver for the ground collision avoidance tests. For automated maneuvering, using the aircraft autopilot, available control authority needs to be considered.

iGCAS/SR22 System Integration

The conversion of the iGCAS from the small UAV version to the SR22 went very smoothly. The design for tailoring iGCAS to the SR22 for the manual avoidance maneuver required roughly 20 hours of engineering labor. This included: analysis of the characterization flights; algorithm modifications to account for a pilot reaction time, adding a full envelope SR22 climb rate model and the zoom climb of the Chandelle maneuver; and tuning of the trajectory. Verification and validation of the modified iGCAS took another 20 hours of engineering labor.

Installation of the system onto the SR22 was accomplished by a NASA team that had no previous GCAS experience. Travel restrictions did not allow for the design and integration teams to meet face to face. Integration coordination was limited to delivery of the phone and its associated interface control document and a few teleconferences and phone calls. The integration team took roughly 10 working days to develop and implement the hardware and software integration.

iGCAS/SR22 Collision Avoidance Evaluation

Collision avoidance runs were flown against a singular area which would be classified as hilly to mountainous terrain (see Figure 22). The terrain was a complicated set of features: approaching perpendicular to two parallel ridge lines a half mile apart, the closest roughly a 1000 rise and the farthest a 1300 foot rise. The nearest ridgeline had a notch near the aim point allowing access to the tight valley between the two ridgelines. The dark blue line in the figure is the trajectory prediction and the orange cylinders are the scan-cylinders of the terrain scan of the algorithm. The trajectory has been lowered in elevation by the amount of buffer (TCB) we were using for this particular run.

Flight conditions at avoidance initiation for the collision avoidance tests are presented in Figure 23. Initiation conditions ranged from 112 to 154 knots indicated airspeed. Avoidance maneuvers for the evaluation flights were shorter (5 to 20 seconds) than those conducted in the characterization flights so sustained climb could not be evaluated. Also worth noting, the pilot for the evaluation flights was not the same as the pilot for the characterization flights.

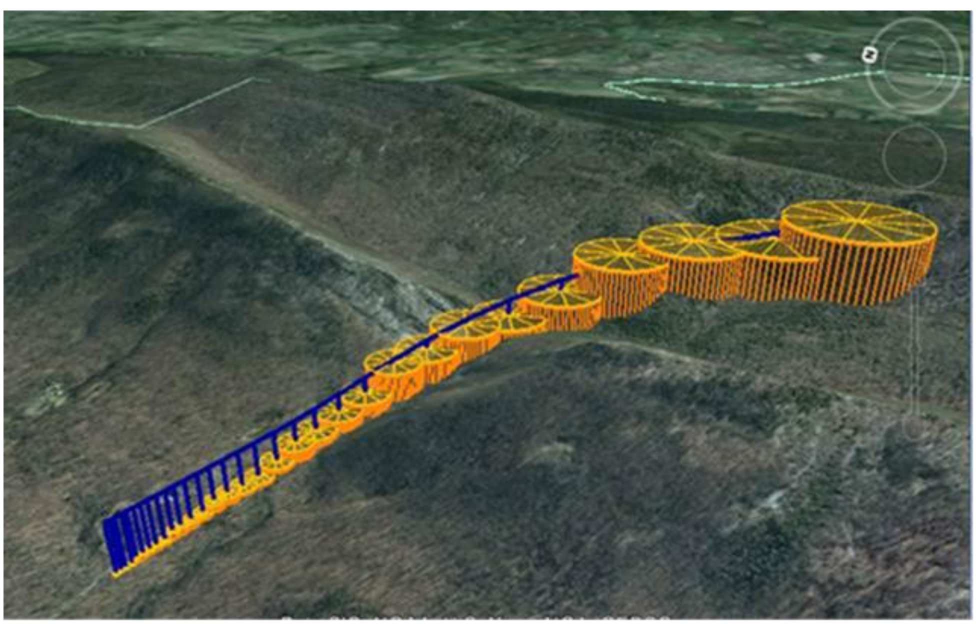

Figure 22. iGCAS/SR22 collision avoidance test terrain with example run.

This opened the door for differences in maneuvers between pilots. Peak zoom climb values for the evaluation flights ranged from 4100 to 2550 FPM, slightly higher than those seen in the characterization flights. However, the scatter of variation between the characterization flights and the evaluation flights resulted in very similar values (see Figure 24). Bank angles achieved were 30 degrees +/- 6 degrees for both left and right turns. Roll rates ranged from 21 d/s to 10 d/s with no discernable differences between left and right maneuvers.

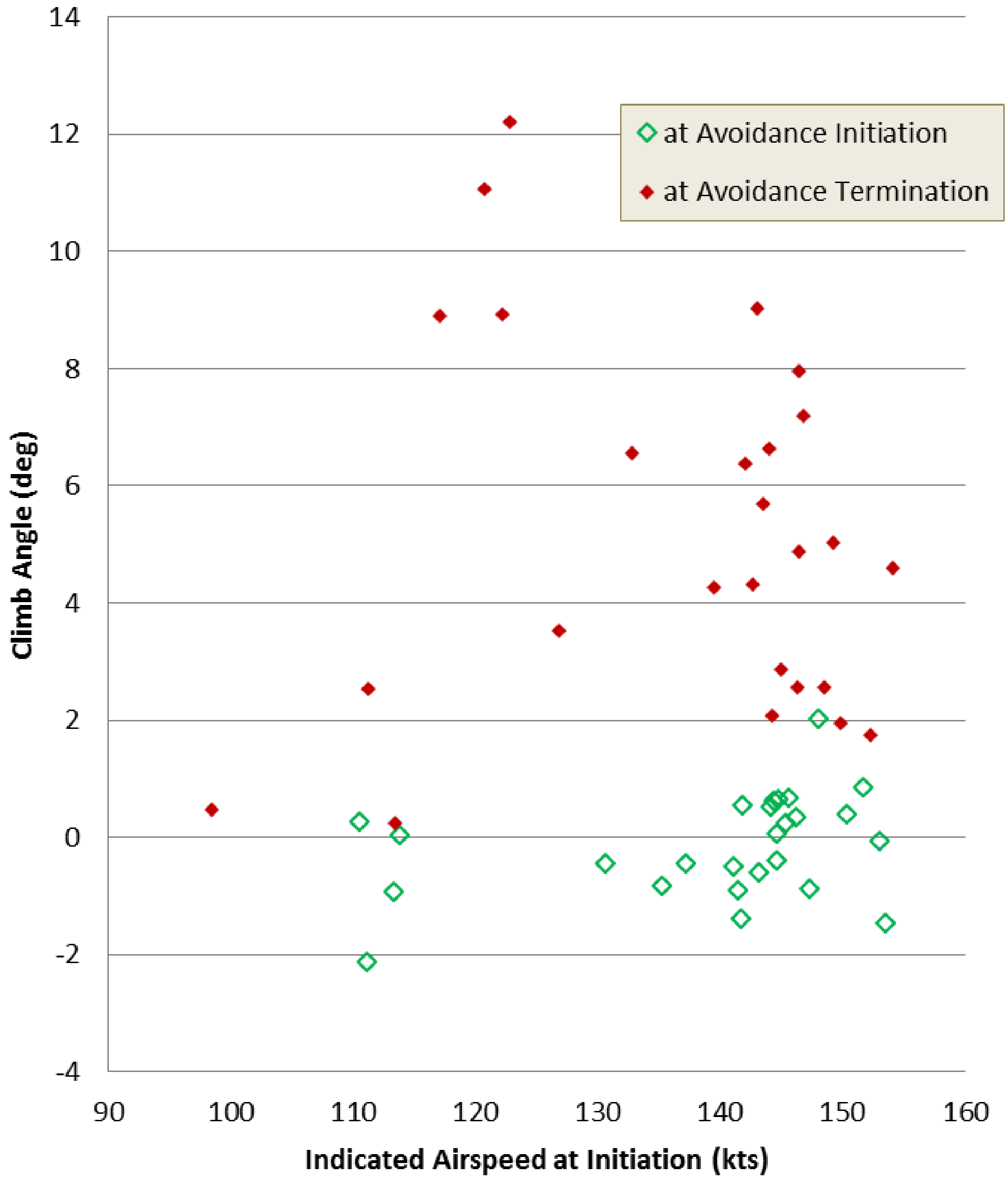

Figure 23. iGCAS/SR22 collision avoidance test conditions.

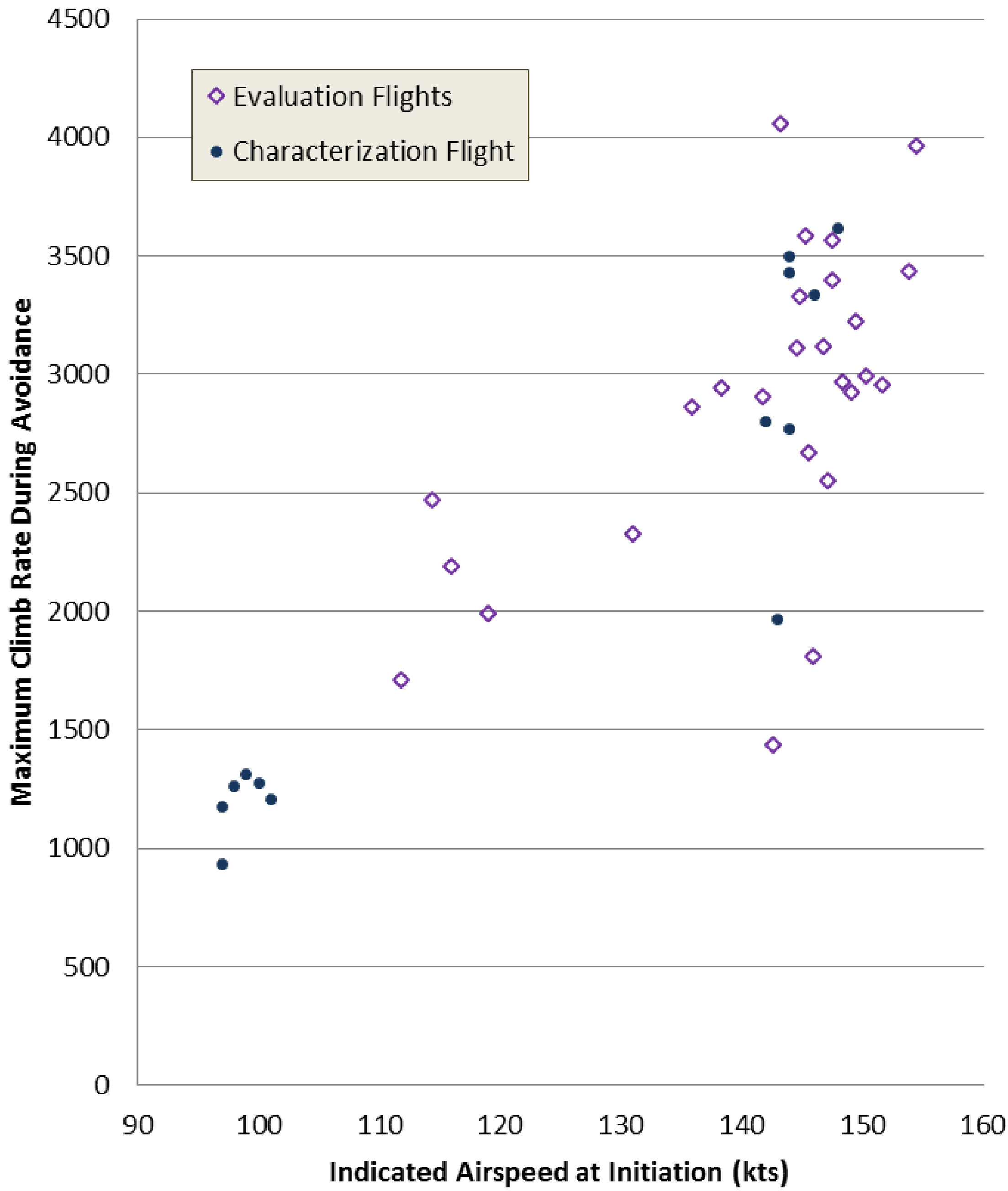

Figure 24. iGCAS/SR22 comparison of peak climb rate during avoidance between characterization and evaluation flights.

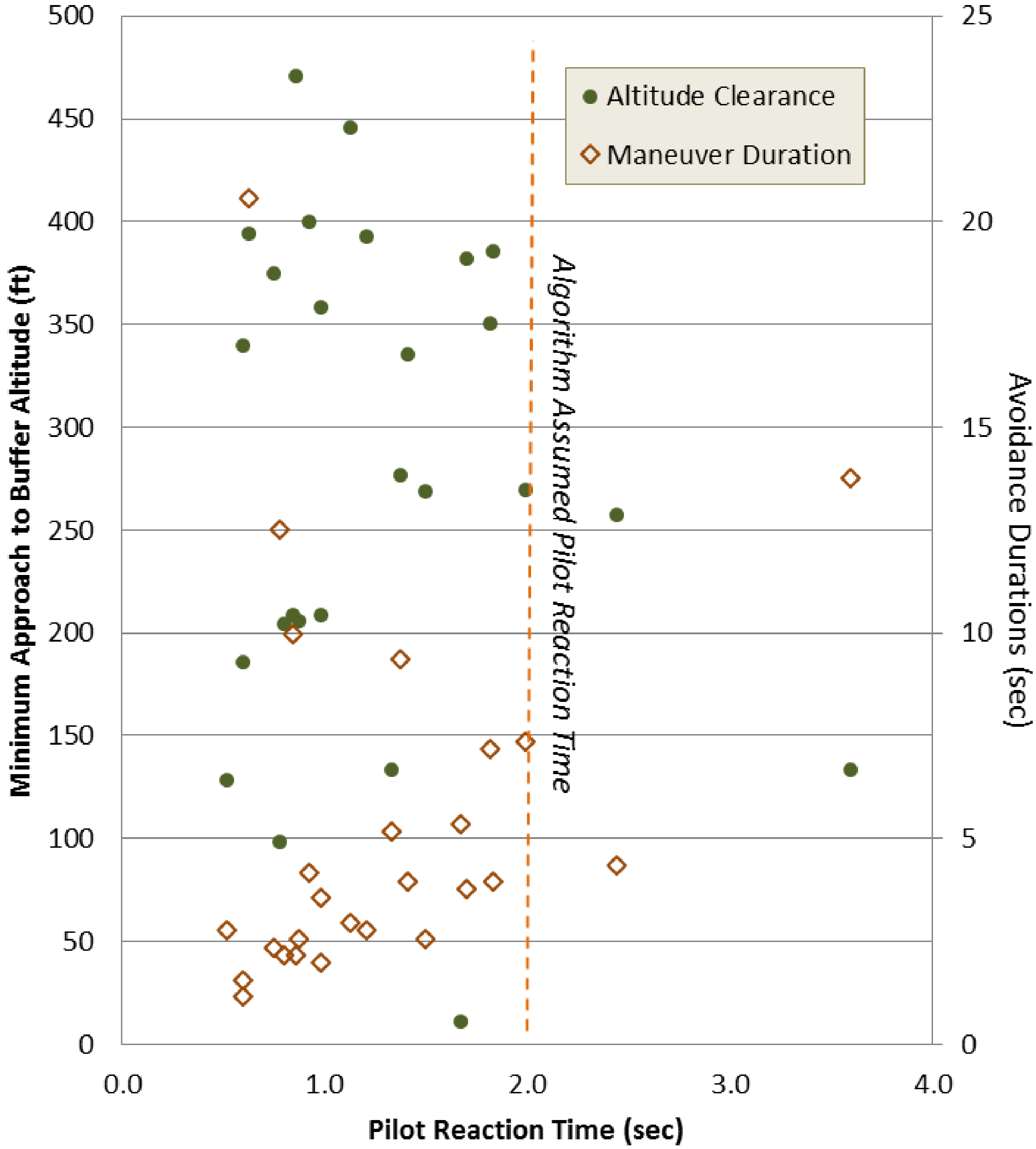

Figure 25. iGCAS/SR22 pilot reaction time, maneuver duration and TCB clearance.

Pilot reaction time for starting to maneuver following the avoidance indication ranged from 0.5 to 3.6 seconds, however the 3.6 second reaction time occurred on the very first run against the feature when test procedures were still somewhat getting worked out. All subsequent pilot reaction times were shorter with only one exceeding the algorithm's allotment of 2 seconds. All runs had satisfactory ground clearance, with altitude above the ground never reaching a value less than the TCB for a given run. Pilot reaction time and associated TCB clearance are presented in Figure 25.

The warning cue for the avoidance was unsatisfactory. The display consisted of 3 arrows, one pointing left, one up and one to the right (see Figure 10). The arrows changed color based on how much time was left until that until that avoidance would no longer clear the terrain. When the last maneuver's time to avoid went to zero it would appear as a hashed arrow (see the left arrow in Figure 10). No effort had been made to develop an appropriate cue as it was beyond the scope of the project. The arrows only displayed what maneuver was to be flown and not how to fly the maneuver. This was marginal for even the test pilots flying the evaluation runs. An untrained pilot not expecting an avoidance command would be much less prepared to respond and less trained on how to execute the requested maneuver.

iGCAS/SR22 Nuisance Evaluation

Two 25 mile legs were flown up and back along the Shenandoah Mountains near the collision avoidance test site to evaluate the nuisance potential of iGCAS. The pilot flew at minimum comfortable altitudes not to break the 500 foot minimum altitude restriction for normal flight. The first leg was flown with a TCB of 0 feet and the second was flown with a TCB of 300 feet. Altitudes above TCB ranged from 860 to 1560 feet and 240 to 1010 for the first and second legs respectively. For the leg flown closest to the TCB, climb rates ranged +/- 800 FPM, airspeed from 114 to 145 knots and bank angles up to 30 degrees and roll rates as high as 28 degrees per second. The iGCAS exhibited satisfactory nuisance free operation issuing no warning over the course of either leg.

Conclusions and Recommendations

A. The Modular Architecture

The iGCAS functionally partitioned modular approach to software architecture provided a highly flexible design that was easily adapted to a wide range of vehicle performance and avoidance maneuver approach. The change from a small and slow remotely piloted vehicle to an F-16 and to a complex two-stage Chandelle avoidance maneuver was accomplished with less than 40 hours of engineering labor. The next step in testing the adaptability of the iGCAS algorithm should be to adapt it to a VTOL/helicopter platform.

B. Collision Avoidance Performance

The iGCAS worked exceedingly well with no penetration of the selected buffer during any of the testing. However, further testing should be conducted across a wider range of terrain and flight conditions to verify the system is functioning properly. The system should be considered for integration onto the MQ-1 and MQ-9 platforms.

C. Nuisance/False Activation/Warning Performance

The system was exceedingly nuisance free over the conditions flight tested. Advantages were seen in all three vehicles evaluated:

1) The UAV testing far exceeded normal low altitude operations to the point that it was considered that a UAV so equipped could be used for missions far lower than what is currently considered.
2) General aviation operation at minimum allowed altitudes (500 feet) can be performed in moderate to rough terrain without nuisance warnings.
3) The algorithm appears to offer further nuisance free capability for the F-16 should it need it.

D. Required Future Work

An appropriate pilot vehicle interface (PVI) must be developed prior to transitioning this technology to the public for use as a warning system. A set of displays must be developed that will both not add to the nuisance potential of the system yet at the same time alert a pilot of the need for an avoidance and direct that pilot through one of three avoidance maneuvers. Furthermore, the interface must allow easy configuring of the system to pilot warning preferences, aircraft mass properties and aircraft type.

The flight tests were accomplished using highly trained test pilots, the display and system performance requirements should be matured through a comprehensive evaluation. Baseline maneuvers should be defined and pilots with varying skill levels should evaluate the displays and system.

Further work should be done to study autopilot integration with iGCAS. Higher authority autopilots are available and should be investigated, thus preserving a path to Auto GCAS for general aviation. The autopilot authority (from low to high) versus pilot alerting to fully automated GCAS should be characterized to determine an appropriate implementation approach.

The system as tested did not provide protection from obstacles. Inclusion of obstacle protection should be addressed through integrating a digital vertical obstacle data base.

Over the 30-plus years of using digital terrain products, it has been found by project personnel that ridgelines in the DTM are generally lower than actual terrain, termed ridgeline clipping. Figure 26 shows the ridgelines in the vicinity of the small UAV tests and that the DTM elevations for these ridgelines average 30 feet lower than the surveyed elevations (indicated by the white balloons in the figure). This phenomena appears to be present in all DTM products investigated and poses condition where DTM based GCAS will not provide protection. The DTM encoding

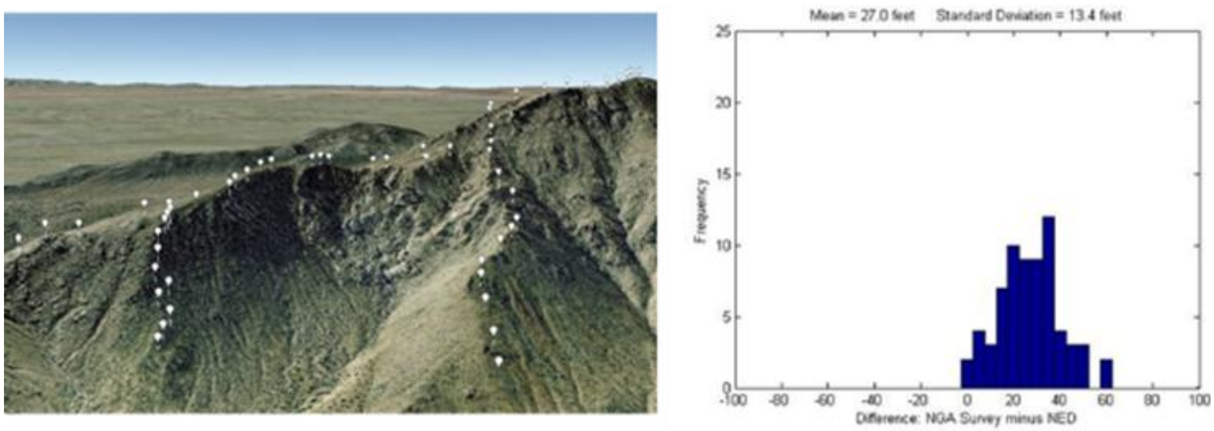

Figure 26. Ridgeline clipping in DTM products.

process offers a means to recover the elevations lost from ridgeline clipping. During a portion of the iGCAS/F-16 work an alternative approach was investigated for the local map in which a feature termed sub-scanning was added. Sub-scanning leveraged the alternative local map and appeared to allow a good degree of ridgeline clipping recapture. These results were not presented in this paper, however the sub-scan technique should be incorporated into future version of iGCAS to cover this gap in all DTM based warning systems.

Finally, the need to feed data to the algorithm in the phone through a USB connection is impractical. Two methods should be investigated to improve this interface:

1) Wireless interface should be developed for the system to take advantage of the newer avionics on the market that support wireless devices.
2) Use of the phone sensors should be investigated to provide a low cost alternative should a wireless capability not be available.

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